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The Search for $n-\bar{n}$ Oscillation in Super-Kamiokande I

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A search for neutron-antineutron ($n - \bar{n}$) oscillation, a process with $|\Delta B| = 2$ that has been predicted by right–left (R-L) symmetric gauge theories, was undertaken using the 24.5×10^{33} neutron-yrs exposure of Super-Kamiokande I, in an analysis that included the significant sources of experimental uncertainties. No evidence for $n - \bar{n}$ oscillation was found, the lower limit of the lifetime for neutrons bound in ^{16}O was determined to be 1.89×10^{32} yrs at the 90% confidence level (C.L.), and the corresponding limit for the oscillation time for free neutrons was calculated to be 2.44×10^{8} sec using a theoretical suppression factor of 1.0×10^{23} sec^{-1}.

PACS numbers:

Searches for Baryon Number Violation (BNV) are motivated by various Grand Unification Theories (GUTs) and by the observation first put forward by A. Sakharov in 1967 that BNV, C, CP violation, and non-equilibrium thermodynamics are needed to explain the Baryon Number Asymmetry of the Universe (BAU) [1]. In the three decades since the first large (5 kton) water Cherenkov and fine grained nucleon decay experiments appeared in the early 1980's, the impetus for studying $|B-L|$ violating interactions such as neutron-antineutron ($n - \bar{n}$) oscillation and double beta decay has grown steadily. The possibility of $n - \bar{n}$ oscillation was first discussed by V. Kuzmin in 1970 [2], and recent experimental limits on $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$ have already ruled out the simplest $|B - L|$ conserving GUTs, minimal SU(5) and the minimal supersymmetric version of SU(5). It has also been shown that the triangle anomalies involving electro-weak bosons wash out any $|B - L|$ conserving baryon asymmetry above the 10 TeV scale. The search for $|B - L|$ violating reactions has become increasingly important as a potential explanation of the observed BAU.

The discovery of neutrino oscillations has renewed interest in theories with Majorana spinors which yield B and L symmetry breaking by allowing $|\Delta(B - L)| = 2$ with $|\Delta L|$=2, as in neutrino-less double beta decay and $|\Delta B|$=2 for $n - \bar{n}$ oscillation. These models include a large class of supersymmetric and R-L symmetric $SU(2)_L \otimes SU(2)_R \otimes SU(4)_C$ theories. Neutron-antineutron oscillation has also been predicted by recent GUTs with large or small extra space-time dimensions [3][4] and by R-L symmetric theories that include the seesaw mechanism to generate neutrino masses [5].

An important property of $n - \bar{n}$ oscillation is its dependence on a six quark operator, with a mass scaling of m^{-5} instead of m^{-2} as in the charged X and Y bosons that mediate nucleon decay in minimal SU(5). Therefore, the observation of a significant $n - \bar{n}$ oscillation signal at Super-Kamiokande would imply new physics at a scale of approximately 100 TeV, a factor of 10 larger than the maximum energies scheduled for study at the Large Hadron Collider (LHC).

The previous best 90 % C.L. lifetime limits for bound neutrons are from IMB with 1.7 and 2.4 $\times 10^{31}$ yrs. [6] in two different analyses, Kamiokande with 4.3×10^{31} yrs. in oxygen [7], and Soudan 2 with 7.2×10^{31} yrs. in iron [8]. The current best limit on the oscillation time of unbound neutrons is given by ILL (Grenoble) as 0.86×10^{8} sec [9]. The lifetime limit for bound neutrons can be converted to the $n - \bar{n}$ oscillation time for free neutrons by the relationship

$$T_{n-\bar{n}} = R \cdot \tau^2_{n-\bar{n}} \tag{1}$$

where $\tau_{n-\bar{n}}$ and $T_{n-\bar{n}}$ are the oscillation time of a free neutron and the lifetime of a bound neutron, and R is the nuclear suppression factor, for which theoretical estimates are given in the literature [22][23]. In this paper, we describe the results of our neutron-antineutron oscillation search in Super-Kamiokande I. No positive signal was observed, but from our data we obtained a lower limit on the lifetime of a neutron in oxygen of 1.89×10^{32} yrs (90% C.L.), which is about 4.5 times larger than the previous highest experimental limits.

Super-Kamiokande is a ring imaging water Cherenkov counter containing 50 ktons of ultra-pure water, located in Kamioka-town in Gifu prefecture, Japan. Descriptive overviews of Super-Kamiokande and technical details are given in the literature [11]. Data were taken by Super-Kamiokande I from May 31st, 1996 to July 15th, 2001, using a fiducial volume of 22.5 kton. The $n - \bar{n}$ oscillation analysis described in this paper used the complete SK-I data set with a livetime of 1489 days.

An antineutron is expected to annihilate quickly with one of the surrounding nucleons and to produce multiple secondary hadrons, mainly pions. The total momentum of the secondaries is nearly zero, except for the Fermi momenta of the annihilating $\bar{n}$ and nucleon, and the total energy is nearly equal to the total mass of the two nucleons. Thus one would expect an isotropic multi-hadron signature with a total energy of about 2 GeV to occur in neutron-antineutron events in Super-Kamiokande, prior to any nuclear interactions.

A detailed Monte Carlo (MC) simulation was formulated for this study. Since the literature on ($\bar{n}$ + nucleon) annihilation in nuclei is sparse, $\bar{p}p$ and $\bar{p}d$ data from hydrogen and deuterium bubble chambers [12][13][14] were used to determine the branching ratios for the annihilation final states. The branching ratios included in our simulations are displayed in Table I. The values of kinematic quantities in our MC were determined using relativistic phase-space distributions that included the Fermi momentum of the annihilating nucleons. Pions and omegas produced in the $\bar{n}$-nucleon annihilations were propagated through the residual nucleus. This study used a program originally developed for the IMB experiment to simulate meson-nucleon interactions [6]. The cross sections for the pion-residual nucleus interactions were based on an interpolation from measured pion-carbon and pion-aluminum cross sections to those for pion-^{16}O interactions. Excitation of the Δ (1232) resonance was the most important effect in the nuclear propagation phase. It was assumed that the pion and omega cross sections scaled linearly with matter density, a quantity that decreases as the mesons move away from the

annihilation point and exit from the nucleus. The Fermi momentum of the interacting nucleon and the possibility of Pauli blocking were also included in our simulations. We found that 49% of the pions did not interact, while 24% were absorbed and 3% interacted with a nucleon to produce an additional pion or occasionally two more pions, and the rest of the pion interactions involved scattering. These interaction probabilities yielded total and charged pion multiplicities of 3.5 and 2.2, respectively, with an average charged pion momentum of 310 MeV/c and an RMS width of 190 MeV/c. There was a probability of 0.56% that an event included an ω^0 that emerged from the nucleus without having decayed. The final states of the nuclear fragments were calculated using an algorithm based on a simulation from ORNL [15]. Fragments of the residual nucleus that contained two or more nucleons were not simulated in water, since most of the nucleons in these fragments had momenta that were below the threshold for inelastic hadron interactions. Therefore only free n and p fragments were propagated through water.

Since the largest source of background events for $n - \bar{n}$ oscillation is atmospheric neutrinos,we prepared a large MC event sample that corresponded to an atmospheric neutrino exposure of 500 yrs. A detailed description of this simulation is given in reference [16]. The propagation of particles and Cherenkov light in the detector was modeled by a program that is based on the GEANT-3 [17] package. The detector geometry, the generation and propagation of Cherenkov radiation from charged particles, and the response of the PMTs and data acquisition electronics were also included in our simulations. Hadron interactions were simulated using the CALOR package [18] for nucleons and charged pions with p_π >500 MeV/c, and through a custom-made program [19] for charged pions of p_π <500 MeV/c.

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

TABLE I: The branching ratios for the $\bar{n}$+nucleon annihilations in our simulations. These factors were derived from $\bar{p}p$ and $\bar{p}d$ bubble chamber data[12][13][14].

The trigger threshold for our search corresponds to a 5.7 MeV electron signal and yields a trigger rate of about 10 Hz. The background triggers are mostly due to inherent radioactivity in the detector and to cosmic ray muon interactions. Most of the cosmic ray muon events are rejected by a requirement that there be no significant activity in the outer detector of Super-Kamiokande. We also require that the reconstructed visible energy be greater than 30 MeV to remove the remaining low energy radioactivity. This constraint is also necessary to maintain the effectiveness of the event reconstruction. The reduction algorithms are identical to those used for the atmospheric neutrino analyses and nucleon decay searches [16].

Events remaining after the reduction procedure are processed by the full reconstruction program, which yields an overall event vertex, the number of Cherenkov rings, and a direction, particle identification determination, and a momentum for each ring [16]. For $n - \bar{n}$ oscillation events the vertex resolution is 26 cm. Each Cherenkov ring is identified as being either "showering" (e, γ) or "non-showering" (μ, π, p) based upon its hit pattern and opening angle. The momentum is subsequently determined using the assigned particle type and the number of collected photo-electrons inside a cone with an opening half-angle of 70 degrees after corrections for geometric effects and light attenuation are made. Our choice of cone angle completely covers the Cherenkov cone in water, which has an opening half-angle of about 42 degrees. In multiple-Cherenkov ring events, we estimate and separate a sample of photo-electrons for each ring using an expected Cherenkov light distribution.

To isolate $n - \bar{n}$ candidates we apply additional criteria to the reduced fully contained (FC) event sample which is used for our atmospheric neutrino analyses [16]:
(a) The number of Cherenkov rings > 1, (b) 700 MeV $<$ Visible energy $<$ 1300 MeV, (c) 0 MeV/c $<$ Total momentum $<$ 450 MeV/c and (d) 750 MeV/c^2 $<$ Invariant mass $<$ 1800 MeV/c^2. The total momentum is defined as $P_{tot} = |\sum_i^{all-rings} \vec{p_i}|$, where $\vec{p_i}$ is the reconstructed momentum vector of the i-th ring. The invariant mass is defined to be $M_{tot} = \sqrt{E_{tot}^2 - P_{tot}^2}$, while the total energy is defined as $E_{tot} = \sum_i^{all-rings} \sqrt{{p_i}^2 + {m_i}^2}$, where m_i is the mass of i-th ring assuming that showering and non-showering rings are from γ rays and charged pions, respectively. The selection criteria given above were optimized to maximize the ratio $\epsilon/\sqrt{b}$, where ϵ is the signal detection efficiency and b is the number of background events.

Distributions of the four reconstructed kinematic variables are displayed in Figure 1. Our atmospheric neutrino MC includes the effects of ν_μ to ν_τ neutrino oscillations, with mixing parameters of ($\sin^2 2\theta$, Δm^2)=(1.0, 2.1×10^{-3} eV^2) obtained from our previous publication on this topic [16]. Figure 1 (b) shows the visible energy distribution after an event selection criterion based on the number of Cherenkov rings was imposed. The average visible energy for $n - \bar{n}$ MC oscillation events is about 700 MeV, much smaller than twice the nucleon mass. This decrease is mainly due to loses in hadronic energy as the result of scattering and absorption interactions with nuclear matter in the water.

Application of the event selection criteria (a)-(d) yielded 24 candidate events, a detection efficiency of 12.1% from the remaining $n - \bar{n}$ MC events in the final sample, and 24.1 background events as estimated for the 1489 days of Super-K I. Final event samples are displayed as scattered dots inside of the box-shaped scatterplots that apply criteria (c) and (d) in

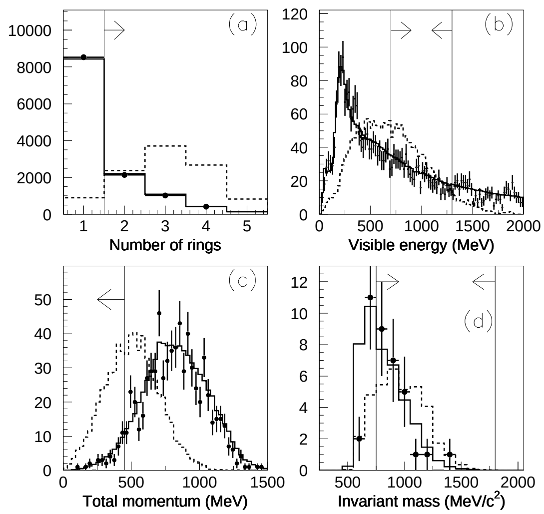

FIG. 1: Distributions of the kinematic variables subject to additional criteria at each of the reduction steps described in the text including: (a) Number of rings, (b) Visible energy, (c) Total momentum, and (d) Invariant mass. Circles indicate data points with statistical error-bars, solid black lines and dashed lines represent the atmospheric neutrino MC and the $n-\bar{n}$ MC, respectively. Light vertical lines with arrows indicate the event selection criteria.

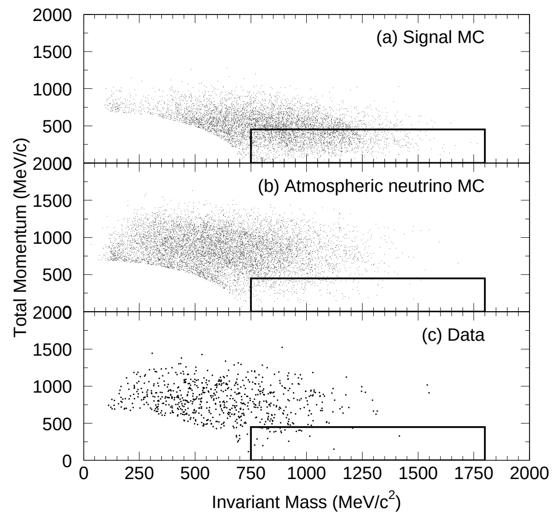

FIG. 2: Total momentum vs. the invariant mass after applying selection criteria (a) and (b) on the FC sample: (a) Signal MC, (b) atmospheric neutrino MC, and (c) Data.

Figure. 2. Of the remaining background: 57.8% comes from multi-hadron production by Deep Inelastic Scattering (DIS), 31.4% from single pion production via resonances, and 5.5% from single η and K meson production via resonances. The remaining 5.2% of the background results from Charged Current (CC), Quasi-Elastic (QE) scattering and Neutral Current (NC) elastic scattering accompanied by energetic knocked-out nucleons in the water.

Uncertainties in the detection efficiency, exposure, and background rates are given in Table II. The major sources of errors in the detection efficiency are the results of uncertainties in the models for propagation of pions and omega mesons through the residual nucleus. In particular, the error due to uncertainties in the π-nucleon cross section is 20.0%, as estimated from the π-^{16}O scattering data shown in [6] and by comparing results from two independent nuclear interaction programs originally developed by IMB [6] and by Kamiokande [7] (6.1%). The uncertainty from the ($\bar{n}$ + nucleon) annihilation branching ratios is estimated to be 4.6% by comparing different MC results based on variations in the assumed branching ratios [25][26]. The 0.6% asymmetry in the detector gain and the 2.0% difference in the energy scale between the data and the MC affect the momentum cut and contribute 1.7% and 0.4% uncertainties, respectively. By comparing real data with MC events we estimate that the uncertainty in the Cherenkov ring finding procedure is 2.2%. The detection efficiency is estimated to have a total uncertainty of 22.9% while the exposure uncertainty was found to be 3.0% through an estimate of the error in the calculation of the effective fiducial volume. The uncertainties in the atmospheric neutrino flux, the atmospheric neutrino energy spectrum, and the components of the atmospheric neutrino flux contribute 7.8% to the systematic uncertainty of the background rate. The DIS cross section uncertainty in the low q^2 region yields a large contribution to the uncertainty in the background rate, which is estimated to be 14.1% by comparing the results from two different parameterizations of the parton distribution functions [20][21]. The uncertainty in the energy scale, the lack of perfect uniformity in the PMT gain, and the uncertainty in the Cherenkov ring finding contribute a total of 14.9% to the systematic errors. The total systematic uncertainty in the background rate is estimated to be 23.7%.

No significant excess was found in our full 1489 day Super-Kamiokande I data set. The lower limit on the lifetime of a neutron bound inside an oxygen nucleus due to $n-\bar{n}$ oscillation was calculated from the 24 observed candidate and 24.1 expected background events. All of the systematic uncertainties were included in the limit calculation by employing Bayesian statistical methods [27] as follows:

$$P(\Gamma|n) = A\int\int\int \frac{e^{-(\Gamma\lambda\epsilon+b)}(\Gamma\lambda\epsilon+b)^n}{n!} \times P(\Gamma)P(\lambda)P(\epsilon)P(b)d\lambda d\epsilon db. \quad (2)$$

The above normalization constant A in Eq.(2) was determined by imposing the constraint $\int_0^\infty P(\Gamma|n)d\Gamma = 1$ where Γ, $\lambda = NT$, and ϵ are the true values of the event rate, exposure, and detection efficiency, respectively, for $n-\bar{n}$ oscillation, and b is the true mean number of background events. $P(\Gamma), P(\lambda), P(\epsilon), P(b)$ in Eq.(2) are the prior probability density functions, which we assume are Gaussian distributions for λ, ϵ, and b. $P(\Gamma)$ is a flat distribution for $\Gamma \geq 0$

Detection Efficiency

Sources	Uncertainty (%)
Fermi momentum of nucleons	6.2
Annihilation branching ratio of $\bar{n}$+nucleons	4.6
π propagation modeling	6.1
π-nucleon cross section in the nucleus	20.0
Energy scale	1.7
Asymmetry of detector gain	0.4
Cherenkov ring finding	2.2
Total	22.9

Exposure

Sources	Uncertainty (%)
Fiducial volume	3.0
Detector livetime	$<$0.1
Total	$<$3.0

Background Rate

Sources	Uncertainty(%)
$(\nu_e+\bar{\nu}_e)/(\nu_\mu+\bar{\nu}_\mu)$, $\nu/\bar{\nu}$ ratio	0.1, 1.0
Up/down, horizontal/vertical flux ratios	$\ll$1
K/π ratio	3.1
Neutrino energy spectrum ($<$1GeV, $>$1GeV)	6.1,3.6
Neutrino cross sections	
QE	5.8
1-π production	2.4
DIS	14.1
coherent π productions	$\ll$1
CC/NC cross section ratio	5.0
Axial vector mass in QE and 1π production	0.6
Fermi momentum for QE	$\ll$1
π propagation in ^{16}O	4.1
Energy scale	4.8
Asymmetry of detector gain	0.5
Cherenkov ring finding	14.1
Total	23.7

TABLE II: Systematic uncertainties in efficiency, exposure, and background rate.

and 0 for negative Γ. Finally, the limit of the neutron lifetime in oxygen, $T_{n-\bar{n}}$, with the inclusion of systematic uncertainties for $n-\bar{n}$ oscillation at the 90% C.L., is determined from eqs.(3), and (4) as follows:

$$T_{n-\bar{n}} = 1/\Gamma_{limit}, \tag{3}$$

$$C.L. = \int_0^{\Gamma_{limit}} P(\Gamma|n)d\Gamma \tag{4}$$

where C.L.=0.9. The calculated result is

$$T_{n-\bar{n}} > 1.89 \times 10^{32} \text{ yrs.} \tag{5}$$

This lifetime limit for a bound nucleon is converted to the $n-\bar{n}$ oscillation time of a free neutron using Eq. (1). Under the assumption that R in ^{16}O is 1.0×10^{23} sec^{-1}, as predicted by Dover et al. [23], the corresponding limit for a free neutron at the 90% C.L. is

$$\tau_{n-\bar{n}} > 2.44 \times 10^8 \text{ sec} \tag{6}$$

compared to $\tau_{n-\bar{n}} > 0.86 \times 10^8$ sec as was measured by the ILL/Grenoble experiment [9].

The lifetime and deduced oscillation time limits for bound and free neutrons from previous $n-\bar{n}$ oscillation searches using water Cherenkov detectors and iron calorimeters are compared with the new Super-Kamiokande I results of Eqs. (5) and (6) in Table III. These earlier experiments did not include systematic uncertainties in the computation of their final results, as was done for Super-Kamiokande I.

The new results are the first in over twenty years from a large water Cherenkov counter, an improvement over the previous best water Cherenkov limits for bound neutrons (from Kamiokande) by a factor of more than 4.5. Our results may also help to constrain theories of grand unification, in particular those involving R-L symmetry, the seesaw mechanism, and extra dimensions.

Experiment	Super-K I	Soudan2	Frejus	Kamiokande	IMB
Source of neutrons	oxygen	iron	iron	oxygen	oxygen
Exposure (10^{32}neutron·yr)	245.5	21.9	5.0	3.0	3.2
Efficiency(%)	12.1	18.0	30.0	33.0	50.0
Candidates	24	5	0	0	3
B.G.	24.1	4.5	2.5(2.1)	0.9	–
$T_{n-\bar{n}}$ (10^{32}yr)	1.89	0.72	0.65	0.43	0.24
Suppression factor (10^{23}sec^{-1})	1.0	1.4	1.4	1.0	1.0
$\tau_{n-\bar{n}}$(10^8sec)	2.44	1.3	1.2	1.2	0.88

TABLE III: A comparison of the Super-Kamiokande I results with those of previous $n-\bar{n}$ experiments using bound neutrons [6–8, 10]. The equivalent oscillation times for free neutrons were deduced from those obtained directly from bound neutrons using the nuclear suppression factor R and the expression $T_{n-\bar{n}} = R \cdot \tau^2_{n-\bar{n}}$, as in equation (1).

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